THREE ORBITAL TRANSFER VEHICLES N91-18156

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Aerospace Engineering students at the Virginia Polytechnic Institute and State University undertook three design projects under the sponsorship of the NASA/USRA Advanced Space Design Program. All three projects addressed cargo and/or crew transportation between LEO and GEO. Project SPARC presents a preliminary design of a fully reusable, chemically-powered aeroassisted vehicle for a transfer of crew of five and a 6,000-20,000 lb payload. The ASTV project outlines a chemically-powered aeroassisted configuration which uses disposable tanks and a relatively small aerobrake to realize propellant savings. The third project, LOCOST, involves a reusable, hybrid laser/chemical vehicle designed for large cargo (up to 88,200 lb) transportation.

SPACE-BASED AEROASSISTED REUSABLE CRAFT (PROJECT SPARC)

Mission Requirements/Objectives

Project SPARC is designed to transfer crew and cargo between the Space Station at LEO (inclination = 28.5°) and GeoShack at GEO (inclination = 0°). There are three mission scenarios: the "small" mission, a round trip transfer for a crew of five and a 6,000-lbm payload; the standard mission, a round trip transfer for a crew of five and delivery of a 20,000-lbm payload to GEO; and the expendable mission, a one-way transfer of a 28,000-lbm payload to GEO disposing of the vehicle into a higher orbit. Objectives of the project are to design one basic vehicle for all three missions, a reusable aerobrake, and removable components (aerobrake, crew module, and payload bays) to be saved during the expendable mission.

Orbital Mechanics

Hohmann transfers are used for the major impulses required for the mission and a single aeropass is used on the return trip (Fig.1). The minimum altitude of the aeropass is 262,470 ft. Total ΔV required is 22,570 fps, a 26.5% savings over a comparable all-propulsive mission. Total time of flight is 10.6 hr and the synodic period between LEO and GEO is 1.6 hr. A flight summary for the standard mission is shown in Table 1.

Table 1. Flight Plan (Standard Mission)

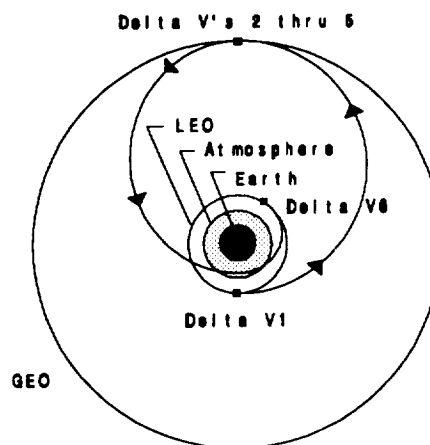| Impulse	Maneuver	Time (hr)/ Delta V (fps)
1	Decircularize-LEO	0/7929
	LEO-GEO flight	5.3/0
2	Plane change (28.5°)	0/2610
3	Circularize-GEO	0/2610
	Minimum stay at GEO	0.4/0
4	Decircularize-GEO	0/4874
5	Plane change (23.82°)	0/2159
	GEO-atmospheric entry	5.2/0
	Aeropass with 4.68° plane change	0.065/0
	Atmospheric exit-LEO	0.077/0
6	Circularize-LEO	0/193
	TOTALS	11.04/22570

Fig. 1. Flight Path

Configuration

The standard SPARC configuration is shown in Fig. 2. Its major components include the truss structure, aerobrake, propellant tanks, a crew module, payload bays, and engines. The main truss structure consists of twelve graphite polyimide networks oriented in a grid pattern to provide maximum support for the vehicle components. The truss structure is designed with the same shape as the aerobrake to facilitate connection of the two, and it is self-sufficient, allowing vehicle operation without the aerobrake. The truss members have outer radii ranging from 1″ to 1.25″ with thicknesses from 0.1″ to 0.89″. All members are connected with titanium silicon carbide joiners.

The aerobrake is constructed with an ellipsoidal nose tangent to an elliptical cone and connected to a toroidal base skirt. The cone is raked at 73° to form a circular base plane 45 ft in diameter. The shell is a rigid graphite polyimide honeycomb sandwich structure supported by graphite polyimide L-beam ribbing mounted flush to the inner surface of the shell at 45° to the longitudinal axis of the base plane. The aerobrake is attached to the main truss structure with graphite polyimide surface mounts. The thermal protection
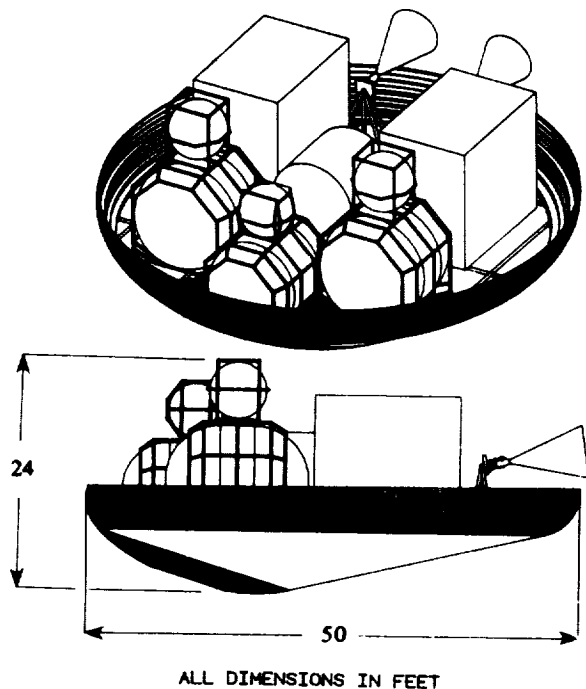
Fig. 2. SPARC Configuration

ALL DIMENSIONS IN FEET

system consists of a reusable, flexible, quilted multi-layer foiled insulation. The outermost layer is a colloidal silica coating supported by quilted aluminoborosilicate (ABS). Ceramic Q-felt is then followed by ten alternating layers of stainless steel foil and ABS scrim cloth. The innermost layer is ABS fabric again, bonded to the aerobrake shell.

The dimensions of the modular payload bays (14.7 ft long, 10 ft wide, and 13.15 ft high) are such that one is needed for the "small" mission, two are needed for the standard mission, and three are needed for the expendable mission. In the case of the expendable mission, the third payload bay would be mounted in place of the crew module. The crew module (total length = 9.5 ft, radius 4.25 ft) has a maximum capacity of five crew for a two-day mission with a two-day emergency reserve. Life support systems include an open atmospheric control system, contaminant removal, thermal management, and cabin pressurization. The cabin is pressurized to 14.7 psia with 80% nitrogen, 20% oxygen. Five extravehicular mobility units and two manned maneuvering units are carried for each mission and three repressurizations are possible. A safe haven provides protection from solar flare radiation.

Propulsion System

Main propulsion is provided by two modified Pratt & Whitney Advanced Expander Engines, each having a mass of 405 lbm and each providing 16,140 lb thrust. The engines use retractable nozzles which reduce the total engine length from

120" to 40" when stowed during aerobraking. A liquid oxygen/liquid hydrogen propellant is contained at 18 psia, and propellant requirements for each mission are as follows:

"small:"	53,930 lbm
standard:	79,753 lbm
expendable:	71,951 lbm

The main tanks (two fuel, one oxidizer) are designed with the volumetric capacity of the expendable mission, and can therefore accommodate the "small" mission as well. For the standard mission, three smaller spherical auxiliary tanks are added to accommodate the higher propellant requirements, and all tanks are fully reusable. Propellant is carried to the engines through lines which run underneath the main truss structure. Attitude and orientation control is provided by 24 30-lb reaction control system (RCS) thrusters arranged in four packs on the perimeter of the truss structure. The RCS uses a hydrazine monopropellant pressurized by nitrogen.

Docking Scenario

The general docking scenario at the Space Station and at GeoShack consists of the following: (1) maneuvering the vehicle into the docking area with the RCS; (2) attachment to three structural support arms (one fixed and two retractable); (3) removal of payload and crew with an offloading arm capable of reaching all vehicle components; (4) detachment of the aerobrake when necessary with four small aerobrake removal arms; and (5) vehicle storage. It is assumed that there is a hangar and air lock at the Space Station and GeoShack. The docking design is shown in Fig. 3.
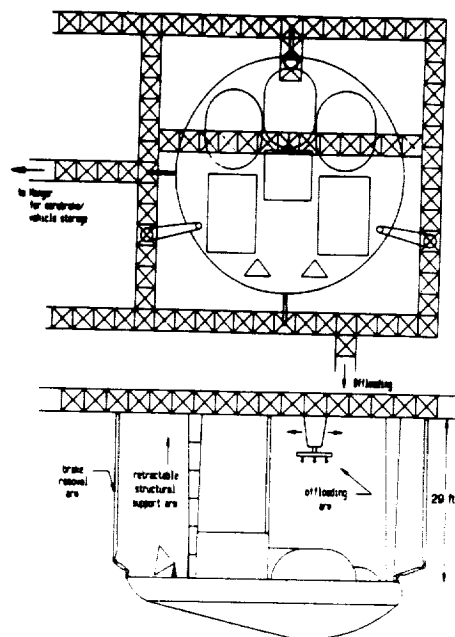

Fig. 3. Docking Scenario

Calculations and Performance Characteristics

Vehicle design and performance calculations included: (1) orbital mechanics; (2) atmospheric heat loading and perigee altitude obtained from an approximate solution by Desautel; (e) nozzle flow calculations obtained from Naval Ordinance Test Station (NOTS); (4) tank insulation and boiloff; (5) aerodynamic and longitudinal stability calculations using modified Newtonian Theory; (6) center of gravity; (7) mass moments of inertia; (8) RCS characteristics derived from the mass moments of inertia values; (9) crew module and payload bay radiation protection; and (10) structural analyses obtained from Structural Analysis Software for Microcomputers (SASM).

The SPARC performance characteristics are listed in Table 2.

Conclusions

Our report has summarized the design specifications of Project SPARC, and results of this design indicate that an aeroassisted vehicle is an attractive mode of orbital transfer. It is expected that the required technical advances in turbomachinery, materials, thermal protection, and other areas will be completed by the time the Space Station is operational, justifying the continuation of research and development of these transfer vehicles.

An approximate analysis of projected costs for the thirty mission life ASTV using (a) reusable tank configuration and (b) disposable tank configuration (with $1000 per lb cost of delivery to LEO projected for 2010) indicated that significant savings can be realized with a disposable tank version.

A typical mission originates at the Space Station with a separation maneuver and a phasing orbit injection followed by an approximate Hohmann elliptical transfer to GEO. Upon reaching GEO, circularization and the 28.5° plane change will be accomplished via single ΔV impulse. At GEO, the vehicle will rendezvous with the GeoShack and the payload will be deployed during which time the ASTV will receive life support from the GeoShack. While in GEO, the vehicle will be able to reach one or more locations for repair or service of satellites and spacecraft. The transfer from GEO back to LEO will begin with a deorbiting impulse to bring the vehicle back into the Earth's atmosphere and to make the plane change from 0.0° to 26.3° inclination. Upon entering the atmosphere, the vehicle will use the lift and drag generated by the aerobrake to achieve the remaining 2.2° of inclination and a decrease in speed of 7690.6 ft/sec. After exiting the atmosphere, the vehicle is placed into a phasing orbit at 350 miles followed by a final Hohmann transfer to LEO.

Figures 4 and 5 show a typical ASTV configuration. Shown are the reduced size aerobrake, the large disposable tanks, and the mission modules. A mass breakdown is provided in Table 3.
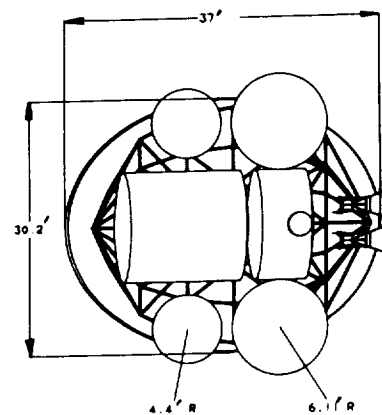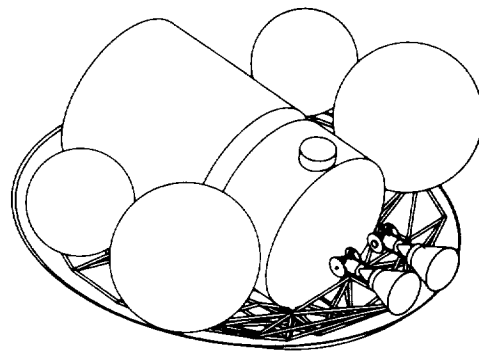
Table 2. SPARC Performance Characteristics

Characteristic	Small	Standard	Expend.
Propulsion:			
Main engine I_{sp} (sec)	487	487	487
Propellant flow rate (lbm/sec)	35.86	35.86	35.86
Main engine thrust (lbf)	16,140	16,140	16,140
Mixture ratio (W_o/W_t)	6/1	6/1	6/1
RCS I_{sp} (sec)	225	225	225
RCS thrust (lbf)	30 each	30 each	30 each
Masses (lbm):			
Vehicle dry mass, M_s	18,577	20,535	13,469
Payload, LEO-GEO, M_{11}	6000	20,000	28,000
Payload, GEO-LEO, M_{12}	6,000	0	N/A
Propellant used LEO-GEO, M_{p1}	40,627	68,960	71,951
Propellant used GEO-LEO, M_{p2}	13,303	10,793	N/A
Performance:			
Payload-Mass ratio, LEO-GEO $\{M_{11}/(M_{p1}+M_s)\}$	0.101	0.233	0.328
Payload-Mass ratio, GEO-LEO $\{M_{12}/(M_{p2}+M_s)\}$	0.188	0.0	N/A
Structural coefficient	0.256	0.205	0.158

AEROBRAKING SPACE TRANSFER VEHICLE

The Aerobraking Space Transport Vehicle (ASTV) is a cost effective, reusable orbital transport vehicle to be used in conjunction with the space shuttle, the Space Station, and the GeoShack to transport a payload and/or a crew between the Space Station and the GeoShack.

Three mission scenarios are: (1) deliver 6000 lbm round trip, (2) deliver 20,000 lbm to GeoShack and return empty, and (3) deliver 28,000 lbm to GeoShack and dispose of the vehicle into a higher orbit. The main objectives used as a guide driving the ASTV design process were: (1) reliability and safety, (2) minimize mission costs, and (3) maximize flexibility.

Fig. 4. ASTV Configuration

Fig. 5. ASTV Isometric View

Table 3. Vehicle Mass Breakdown

Components	Mass, lbm
Aerobrake System:	
TPS	600
Backing Support (Al)	1,400
Ribbing (Al)	1,250
Frame	1,866
Rails	1,132
Propellant Tanks	1,352
Main Engines	740
RCS	1,320
Propellant Handling	700
Electrical Power	912
Communications	497
GN & C	91
Cargo Modules (2)	1,110
Crew Module	4,890
Cargo	14,000
Total Dry Mass	31,860

The propellant selected for both the main engines and the RCS system is liquid hydrogen/liquid oxygen. The propellant requirements of all three missions are shown in Table 4. These values include a reserve in the event of an emergency return.

Table 4. Propellant Requirements

Mission	Propellant (lbm)
1	50,449
2	62,960
3	59,056

The raked cone aerobrake overall dimensions are shown in Fig. 6. The structure of the brake consists of aluminum-lithium alloy stringers riveted to an aluminum skin. The thermal protection for the aerobrake is provided by a multilayer insulation consisting of aluminoborosilicate cloth, insulation, and stainless steel foil separated by scrim cloth. A one-foot skirt was added around the top of the brake. During the aerobraking maneuver, the aerobrake will provide a .23 L/D at an angle of attack of 13.25° and a maximum deceleration of 3.72 g.

The ASTV main propulsion is provided by two side-by-side engines developing 15 klbf thrust each. These engines have a chamber temperature of 6,660°R, a chamber pressure of 3,000 psi and a nozzle area ratio of 650 resulting in a specific impulse of 498 sec. The turbomachinery consists of a four-stage, centrifugal hydrogen pump driven by a two-stage, axial flow hydrogen turbine and a single-stage, centrifugal oxygen pump driven by a single-stage, axial flow hydrogen turbine.

The engine features a retractable nozzle in which the 33-in extendable portion is retracted prior to the aerobraking maneuver. The engine mounts have electric motors for gimballing in pitch and propellant driven actuators for gimballing in yaw. The minimum and maximum pitch angles are -40° and 18° respectively, while the minimum and maximum yaw angles are ±7.5°. Fig. 7 shows the engines rotated to extreme angles in actual operation and Fig. 8 shows them in the stowed position.
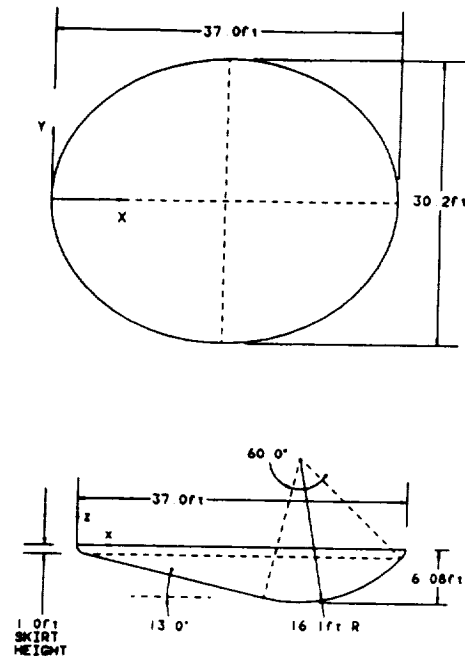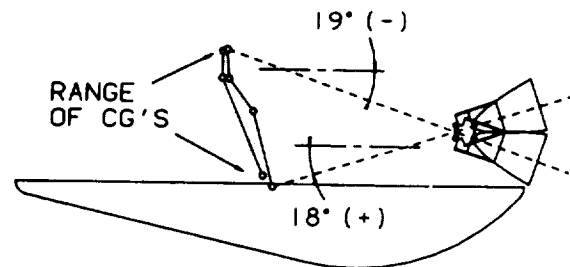
Fig. 6. Aerobrake

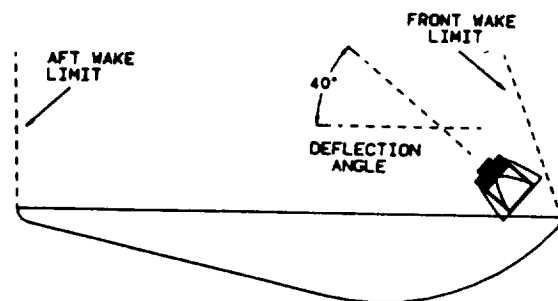Fig. 7. Thrust Vectoring Through Extreme CG Locations

Fig. 8. Engines in Stowed Position

The ASTV comprises four major structural components: a frame, mission modules, propellant tanks and aerobrake supporting structure. The frame is composed of HT graphite/epoxy composite tubes and one square member that are joined at 65 nodes by aluminum endfittings (Fig. 9). Two 27-ft-long aluminum rails are used as a cradle for the mission modules. The frame is connected to the aerobrake via aluminum attachment accessories connected to 11 "Z" type aluminum-lithium stringers.

The propellant tanks fall into two categories: disposable and reusable. There are four large disposable tanks pressurized to 20 psi: two hydrogen and two oxygen tanks. These tanks will be detached by using explosive bolts and a solid rocket motor. A solid shield protects the craft from the rocket blast. The permanent tanks consist of five hydrogen and five oxygen tanks pressurized to 500 psi by a helium-filled bladder. These tanks contain propellant responsible for all maneuvers following the aeropass plus reserve. Insulation and impact protection are provided by stainless steel foils interleaved with Nextel (MLI).

Mission payloads are carried in 8-ft-long by 14-ft-diameter cylindrical cargo modules made of aluminum-lithium. The cargo modules provide mounting platforms, impact and radiation protection and selective positioning for the payload. Up to three modules may be connected to form one 24-ft-long unit, or all three modules could be individually capped, and of course other combinations of modules can be used to fit the needs of the cargo. The cargo modules are mounted to the rails which have connection points spaced at eight-in intervals so that the modules may be connected in a wide range of positions along the length of the rails and thereby adjust the c.g. location.

The crew module is basically a cargo module designed for human transport. The crew module shares the same overall dimensions as the cargo modules so that it too may be connected to other modules and moved around within the ASTV. The crew module can support three adults in an ideal Earth atmosphere for 48 hours with the capability for one full repressurization. A solar flare shelter and a thermal control system are included in the design.
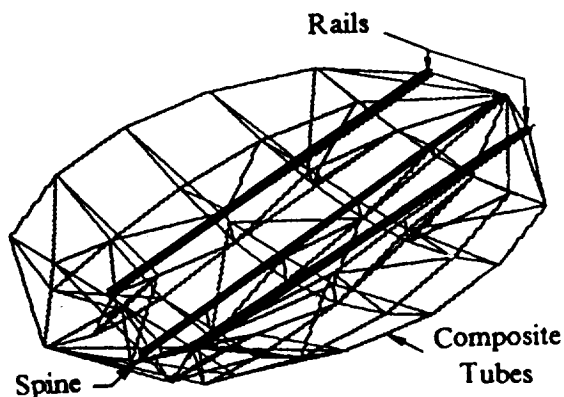
Reaction Control System (RCS) comprises two different sizes of thrusters, 60 lbf and 10 lbf. Overall there are 50 thrusters (34/60 lbf and 16/10 lbf providing double redundancy) located in four clusters around the top of the aerobrake. The clusters are mounted to retractors which draw them inside the aerobrake when not in use.

Navigation is performed by an autonomous inertial system having interfaces with the ground or space stations.

Communication data is transmitted and received to/from the ground, the space shuttle, and the Space Station via K band link.

The electrical power is generated by two 4 kW LOX/LH$_2$ fuel cells (three during manned missions). The oxygen and hydrogen are drawn from the small permanent tanks. Two nickel/hydrogen batteries are also included.

LASER OR CHEMICAL HYBRID ORBITAL SPACE TRANSFER (PROJECT LOCOST)

Mission Requirements/Objectives

Project LOCOST is an unmanned vehicle that utilizes a hybrid laser/chemical propulsion system to transfer cargo between the Space Station at LEO (inclination $= 28.5°$) and the GeoShack at GEO (inclination $= 0°$). The baseline mission scenario is to transfer 20,000 kg of cargo out to GEO and bring 6,000 kg back to LEO. A scenario in which the maximum 40,000 kg of cargo is transferred each way is also analyzed. The laser propulsion system is powered by a Laser Power Station (LPS) orbiting at an altitude of one Earth radius and an inclination of $0°$. The basic LOCOST specifications are listed in Table. 5.

Table 5. LOCOST Basic Specifications

Orbit Transfer Time	2-3 weeks
Cargo Mass	20,000-40,000 kg
Laser Type	Direct Solar Pumped Iodide
Laser Wavelength	1.313 μm
Laser Power	12 MW
Chemical Rockets	$I_{sp} = 480$ sec
Laser Rocket	$I_{sp} = 1500$ sec
Technology Level	2010

Orbital Mechanics

The laser propulsion system is used to transfer between LEO and GEO on a spiral trajectory. The chemical system is used for circularizations and plane changes. Two Energy Relay Units (ERU), placed 120° ahead of and behind the LPS, allow continuous power for the LOCOST while the LPS is not blocked by the Earth's shadow. A summary of the baseline mission analysis is presented in Table 6.

Fig. 9. ASTV Frame

Table 6. Baseline Mission Analysis

Flight Segment	Delta V (km/s)	Time (days)	Propellant (kg)
Transfer	5.16	9.63	36,393
Circ.	.00575	.0011	1,018
Plane Ch.	1.52	.025	22,879
Plane Ch.	1.52	.0014	12,879
Transfer	3.17	1.74	6,522
Circ.	1.52	.008	7,414

Cargo Transfer	.6 days
Total Trip Time	12 days
Laser Propellant	43,202 kg
Chemical Propellant	44,020 kg

Thrusting Times:	Laser	83%
	Chemical	.4%
	Coasting	17%

Configuration

The LOCOST configuration is shown in Figs. 10, 11, and 12.

The major components of the LOCOST are: the main truss, optical system, engines, tanks, and payload module.

The main truss is a rectangular frame 29.11 m × 6.3 m × 18.9 m constructed from 6.3-m truss boxes. The support structure for the mirror assembly extends up 9 m from the top of the main truss. Individual truss members are made from graphite epoxy tubular elements (5.4 cm OD, 5.08 cm ID) joined with titanium fittings.

The payload module is composed of a magnesium alloy cylinder to hold the cargo. The LOCOST has the option of a removable payload canister and a detachable payload module. This allows for greater cargo carrying flexibility and easier transfer.
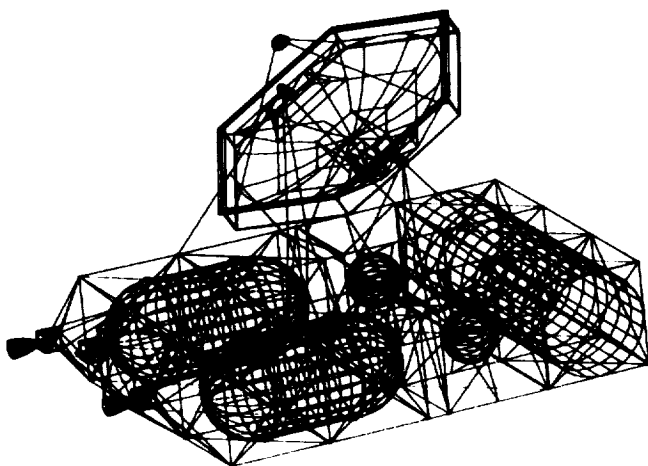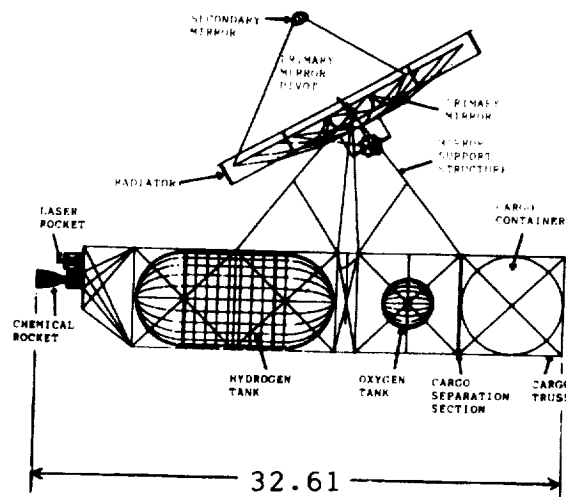

Fig. 11. LOCOST Side View
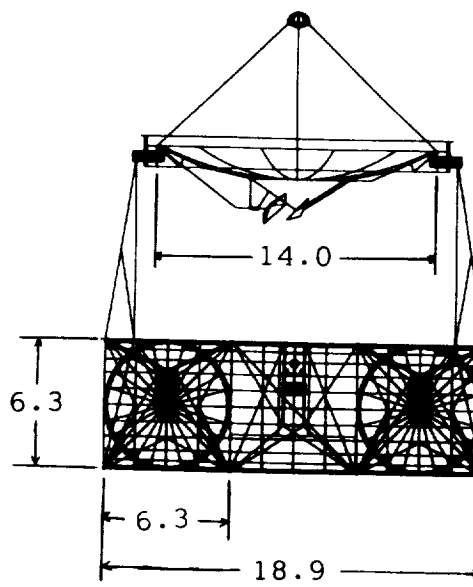

Fig. 12. LOCOST Rear View

Fig. 10. LOCOST Isometric Schematic

Optical System

The optical system consists of a 14-m-diameter concave parabolic primary mirror and a 1.1-m-diameter convex parabolic secondary mirror arranged in a Cassegrain system. Mirrors 3 and 4, attached to the back of the primary mirror, redirect the laser beam to mirror 5. Mirror 5 redirects and focuses the beam into the laser engine. The entire primary mirror structure pivots through 180° to allow for laser beam collection independent of the vehicle orientation (Fig. 13). All mirror surfaces are dielectrically coated. Mirrors 2, 3, and 4 are cooled by a heat pipe system. Mirror 5 is cooled by hydrogen propellant.
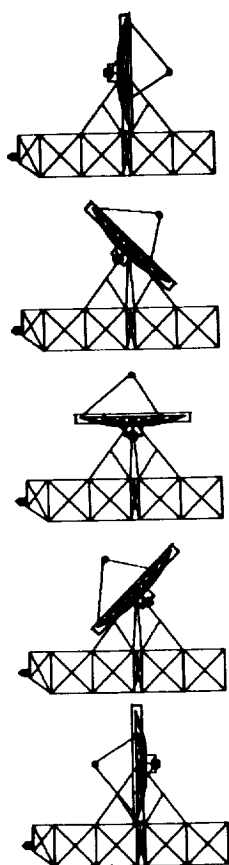
Fig. 13. Primary Mirror Rotation

Vehicle Characteristics and Performance

Vehicle design and performance calculations included: (1) orbital mechanics; (2) optical system analysis using ray tracing techniques; (3) laser engine performance evaluation; (4) cooling analysis; (5) chemical engine nozzle flow calculations obtained from NOTS; (7) tank insulation and boiloff evaluation; (7) mass and moments of inertia calculations (8) structural analysis obtained with SASM; (9) thermal analysis; (10) estimates of RCS and CMG characteristics derived from the mass and moments of inertia values, and roll rates of the vehicle. A summary of the LOCOST mass breakdown is given in Table 7.

Table 7. LOCOST Mass Breakdown

	Mass (kg)
Structure	
Main Truss	423
Optical System	
Primary Mirror w/support	2110
Secondary Mirror	90
Mirrors 3,4,5	300
Propulsion	
Chemical Rockets	422
Fuel Lines & Mounts	154
Laser Rocket	75
Fuel Lines & Mounts	75
RCSs & CMGs	1100
Docking	50
Communications	110
Payload Module	1100
Total Vehicle Dry Mass	6682

The LOCOST performance characteristics are listed in Table 8.

Table 8. LOCOST Characteristics

Propulsion	
Laser	
Specific Impulse	1500 sec
Propellant Flow Rate	.0522 kg/sec
Thrust	768 N
Chemical	
Specific Impulse	480 sec
Propellant Flow Rate	5.2 kg/sec
Thrust	25,000 N
Masses	
Vehicle Dry Mass	6682 kg
Payload LEO-GEO	20,000 kg
Payload GEO-LEO	6000
Laser Propellant Used	43,202 kg
Chemical Propellant Used	44,020 kg
Performance	
Payload Mass Ratio	.28

Propulsion

The laser propulsion system employs the inverse Bremsstrahlung process to couple the laser energy to the thermal energy of the hydrogen propellant. The engine produces a thrust of 768 N. The engine is regeneratively cooled and has a planoconvex sapphire window lens to focus the incident laser beam inside the chamber. The engine is mounted inside a mobile rocket basket which allows for thrust vectoring through the vehicle's center of mass.

The chemical propulsion system consists of two symmetrically placed liquid hydrogen/oxygen rockets. Each engine produces a thrust of 25,000 N. The nozzles of the engines gimbal to track the center of mass.

The hydrogen is stored in two cylindrical tanks with spherical endcaps. The oxygen is stored in two spherical tanks. The tanks are insulated and maintained at an internal pressure of 35 kPa.

Attitude and orientation control is provided by four advanced control moment gyroscopes (CMGs) and eight sets of three hydrazine/oxygen RCS rockets.

Conclusions

This report has outlined an initial configuration study of a hybrid laser/chemical orbital transfer vehicle. The study has indicated that the hybrid propulsion system may be attractive for cargo transportation in the LEO/GEO sphere and that further research is justified.